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AN IMPROVED PHASED ARRAY TERMINAL FOR EQUITORIAL SATELLITE CONSTELLATIONS

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Technical Field

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The present invention relates generally to a phased array antenna. More specifically, the present invention relates to a low cost, low profile tracking phased array antenna for use on a commercial satellite terminal for equitorial satellite constellation systems.

Background of the Present Invention

Current non-geostationary satellite technology directed towards the consumer market typically requires a tracking ground terminal. However, the tracking antennas with this current technology are expensive and bulky and, therefore, generally unacceptable to consumers. Current programs, including Ka-band and Ku-band programs require the development of a less costly, lower profile antenna.

These current conventional multi-beam tracking ground terminals, include arrays with mechanisms for steering beams, such as phase shifters and/or gimbles. These arrays further include integrated mechanisms for simultaneously tracking the pointing directions of multiple beams, such as monopulse tracking loops, step scan, and open loop pointing schemes. These conventional tracking phased arrays are too expensive for a consumer market,

primarily because each beam must have a separate set of electronics associated with each element to process the various signals, including many phase shifters and many duplicate strings of electronics. Therefore, the manufacturing costs for these conventional tracking phased arrays are generally beyond that practical for the consumer market whether for use as a fixed antenna or by a user as a mobile antenna.

Additionally, current conventional tracking devices such as small tracking parabolic reflectors provide a possible solution for fixed users.. For multiple beam terminals, multiple reflectors are required with each reflector tracking a specific beam. However, while operative, small tracking parabolic devices have an extremely high profile. To provide a conventional tracking phased array that could be constructed with an acceptable profile, would be prohibitive in cost. Further, these small tracking parabolic reflectors are not a viable alternative for a mobile user because of both their size and cost.

Summary of the Invention

It is an object of the present invention to provide a low profile multiple beam tracking phased array antenna.

It is a further object of the present invention to provide a low profile tracking phased array antenna of a terminal that is for use on a commercial equitorial satellite constellation.

It is still another object of the present invention to provide a low profile tracking phased array antenna for use on either a fixed or mobile consumer commercial satellite terminal for equitorial satellite constellations.

It is still a further object of the present invention to provide a tracking phased array antenna that is suitable for use on a commercial satellite terminal for equitorial satellite constellations and is intended as a consumer product which provides high performance, is relatively inexpensive, and has a low profile.

It is yet another object of the present invention to provide a tracking phased array antenna with an integrated retrodirective mechanism.

It is yet a futher object of the present invention to provide a low cost and low profile antenna that is mechanically scanned in azimuth and electrically scanned in elevation.

In accordance with the above and other objects of the present invention, a novel satellite

antenna is provided. The antenna includes a rotating circular plate for scanning in the azimuth direction. A plurality of radiation elements are interdigitally spaced along the surface of the circular plate to electronically scan in elevation. In a receive mode, a plurality of individual waves are received at the radiation elements. The radiation elements will be rotated such that a wavefront of the intended signal will be in alignment with the major axis of the long elements. A multiplexer device within each element multiplexes the plurality of signals into a single analog signal before the signal is converted to a digital bit stream by an analog to digital computer. The digital bit stream is then passed to a device that transforms the digital bit streams into multiple digital beam forms. The multiple beam forms are then sent to a digital receiver for processing of the information from the signals. Further, a device is provided for digital multibeam forming through FFT techniques which provides retrodirectivity.

These and other features and advantages of the present invention will become apparent from the following description of the invention, when viewed in accordance with the accompanying drawings and appended claims.

Brief Description of the Drawings

FIGURE 1 is a perspective view of a satellite tracking system in accordance with a preferred embodiment of the present invention;

FIGURE 2 is a perspective view of a rotating antenna configuration utilizing slotted waveguides in accordance with a preferred embodiment of the present invention;

FIGURE 3 is a perspective view of a plurality of cross-slotted waveguides for use on an antenna surface in accordance with a preferred embodiment of the present invention;

FIGURE 4 is a schematic diagram of a circuit for intercepting the incoming wave and converting the wave signals to digital streams in accordance with a preferred embodiment of the present invention; and

FIGURE 5 is a schematic diagram of an integrated retrodirective tracking mechanism in accordance with a preferred embodiment of the present invention.

Best Mode(s) for Carrying Out the Invention

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Figure 1 illustrates an environmental view of the disclosed antenna in accordance with a preferred embodiment of the present invention. As shown, a preferred antenna 10 is positioned in a fixed position on the ground and is in communication with a plurality of orbiting satellites 12 to transmit signals thereto and receive signals therefrom. Another antenna 10 is attached to an automobile travelling along the ground which is also in communication with a plurality of orbiting satellites 12 to transmit signals thereto and receive signals therefrom. The disclosed antenna may also be attached to other mobile vehicles such as aircrafts or boats. The satellites 12 are preferably medium earth orbit equitorial satellites.

The preferred antenna 10 is illustrated in Figures 2 through 4 and provides a low cost and low profile configuration that also provides high performance. It should be understood that the illustrated antenna configuration is merely a preferred embodiment for achieving the objects of the present invention and that other configurations that provide low cost, low profile, and high performance may be utilized.

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As shown in Figure 1, the antenna 10 includes a plurality of antenna radiation elements 14

that are positioned on a circular plate 16. The circular plate 16 is a rotating plate that rotates about a center axis, as will be described further herein.

In a preferred embodiment, the rotating plate 16 is less than one inch (1") thick and has a diameter of fifteen inches (15") or less. Obviously, the dimensions of the rotating plate 16 may vary. However, the greater the diameter and thickness, the larger and more costly the antenna 10 will become. As shown in Figure 2, the antenna radiation elements 14 are preferably constructed using a plurality of parallel slotted waveguides 18. However, a variety of different antenna radiation elements may instead be utilized, such as patch arrays. The operation of the disclosed antenna configuration is described in a receive mode only. The corresponding transmission mode operation can be easily understood by one of skill in the art via reciprocity.

In accordance with a preferred embodiment, each slotted waveguide element 18 is approximately 10 wavelengths long. In one embodiment, 16 long waveguide elements 18 are positioned on the circular plate 16. The waveguide elements 18 are grouped into two groups and are interlaced, as shown in Figure 1, such that waveguide 1a and waveguide 1b begin at opposite ends of the circular plate 16 and overlap one another. Each of the individual waveguides are

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preferably separated by one-half wavelength (½ λ). Therefore, the total aperture in which the waveguide elements are positioned is about 10 x 10 wavelength in a square and the expected peak gain of a straight out or boresight beam from this aperture is about 28 to 30 dB. While the circular plate 16 rotates, rotating the antenna radiation elements 14 therewith, the vertical position of the circular plate 16 remains generally stationary. It should be understood that the number of waveguides positioned on the circular plate may vary, however, the preferred number of waveguide elements is between 10 and 20. Further, the distance between the waveguide elements and their length may also vary.

In a receive mode, the array antenna 10 will be rotated in the azimuth such that all slot array elements 18 will be in alignment with the planar wavefront of an intended incoming signal. Consequently, all the slots in a long waveguide element 18 are excited by the same planar wavefront simultaneously.

Each slotted waveguide element 18 has a first end 20 and a second end 22. The first ends 20 are positioned on a surface of the aperture 24 defining the radiation elements, while the second ends 22 are overlapped by adjacent slotted waveguide elements 18 such that the elements are interdigitally spaced. Each waveguide element 18 has a plurality of

cross-slot openings 26 formed on their top surfaces 28. An H-plane septum (a metal plate) 30 is inserted into each waveguide element 18. Each metal plate 30 has a plurality of slanted slots 32 formed therethrough which act as one of the key circular polarization exciting mechanisms.

The waveguide elements 18 operate in a standing wave mode and have an identical fan-beam pattern with a 6° by 150° elliptical beam created through the cross-slot openings 26 on the top surfaces 28 of the waveguides 18. The cross-slotted waveguides 18 and the septum plate 30 are both illustrated in Figure 3. The slanted slots 32 on the septum plate 30 are angled at approximately 45° and when positioned inside each waveguide element 18 will interact with the matching perpendicular cross-slots 26 on the top surface 28 (or E-plane) of the respective waveguide element 18. As a result, an incoming (right-hand) circular polarized wave on the E-plane wall will excite an TE_{01} mode wave inside each waveguide element 18. To receive the opposite (left-hand) polarized wave, the slant angle of the slanted slots 32 on the septum 30 must change to approximately 135° or 45° in the opposite direction. In the preferred embodiment, on a given plate 16 some of the longitudinal elements 18 will have septums 30 with slanted slots 32 at approximately 45° and some of elements 18 will have septums 30 with slanted slots 32 at approximately 135°. It should be

understood that a variety of other types of waveguide elements may be utilized so long as they allow for the formation of multiple beams.

In operation, the circular plate 16 will be rotated to a position such that the wave front of an intended incoming wave is parallel to the central axes of these slotted waveguide 18. The fan beam radiation pattern of each slotted waveguide element 18 will intercept the incoming wave individually, which will then be amplified, filtered, coded, multiplexed, and down converted. As shown in schematic Figure 4, the conditioned signals will be converted to digital streams, which will then be decoded, digital beamformed, and then transferred to a digital receiver. A digital receiver will then convert the received waveform into information signals.

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~~Specifically, as shown in Figure 4, each of the pair of sixteen slotted waveguides 18 will individually intercept an incoming wave. The waves will be intercepted by the phased array elements 18. The top portion of Figure 4 is a schematic of a Ku band receive array. Similar architectures can be utilized for other frequency bands, such as L-band, S-band, and Ka band. Obviously, the present invention may be utilized for each of these frequency bands. As schematically represented by reference numerals 34, 36, the waves received at the waveguide~~

~~elements 18 are processed by circuitry associated with each of the elements. The incoming wave is then amplified by a respective linear amplifier 38 before being passed to a conventional band pass filter 40 where the signal is filtered. After the signal has been filtered, it is then coded at a code generator 42 before being transferred to a multiplexer 44. The multiplexed signal is passed to an amplifier 46 before being multiplexed and then converted to a digital stream 48 by an analog-to-digital converter 50.~~

The code division multiplex technique illustrated in the top portion of Figure 4, reduces the number of components in the down conversion chain as well as the number of analog-to-digital converters. The received signals from the waveguide elements 18 are multiplexed at the multiplexer 44 into a single microwave stream by known CDMA techniques, such as disclosed in U.S. Patent No. 5,077,562. The multiplexing of the multiple signals reduces the number of components necessary to process the signals and consequently reduces the cost of the ground terminals. When operated in a noise dominant (via injection of orthogonal noise before analog to digital conversion), the receiver dynamic range can also be significantly enhanced through the oversampling of the analog to digital converter.

Incorporating these multiplexing techniques, as shown in Figure 4, with known digital beam forming techniques provides improved receive performance in high dynamic range operation environments. It should be understood that conventional analog beam forming may be performed on the signals in accordance with the present invention. However, reducing the number of linear amplifiers 38 and phase shifter electronic sets from 360 elements to 16 elements for a receive antenna is a significant advantage and cost reduction provided by the present invention. The utilization of known digital beam-forming in accordance with the present invention provides further component and cost reductions.

The entire receiving antenna processing is performed through the combination of low profile one dimension radiation elements 14, which are placed in parallel on the circular rotating plate 16. The processing is further accompanied by aligning the long radiating elements 14 along the intended incoming waveform by rotating the circular plate 16 and then performing beam forming in the orthogonal direction by summing up the output signals of the long radiation elements. By processing the signals in this manner, a high performance antenna can be provided with a very low profile circular volume.

Figure 5 illustrates a retrodirective mechanism that is integrated into the low profile

antenna 10, described above, to eliminate the cost of conventional tracking mechanisms, in accordance with another preferred embodiment of the present invention. As shown in Figure 5, the output of the analog-to-digital converter 48 is then input into a plurality of match filters 52, whose outputs are transferred to a digital multibeam beamforming device 54. The digital beams 56 are then transferred to a respective code generator 58 before being multiplexed at a multiplexer 60. The multiplexed beam 62 is then transferred to a digital receiver 64 where the received waveforms are converted into information signals 66.

Similar to the antenna disclosed in the prior figures, the entire receiving antenna and tracking processing of this preferred embodiment is through the low profile, one dimensional radiation elements 14. The radiation elements 14 are again preferably placed in parallel on the circular plate 16 which rotates about its center axis. The long radiation elements 16 are also aligned along the intended incoming waveform by the rotating circular plate 16 and then subjected to multiple beamforming through fast fourier transforms (FFT) at the digital multibeam beamforming device 54. The outputs of the digital multibeam beamforming device 54 through FFT are associated with signals from various directions covered by the different (contiguous) beams. The outputs of the FFT will be fed into a retrodirective

processing mechanism, as described below, to determine where the intended signal is coming from and then to send the transmit signal to the same direction. The low cost tracking is accomplished by retrodirectivity. The history of the beam positioning will be stored in the terminal as a reference for the satellite emphamerie.

The received signals are again multiplexed into a single microwave stream via known CDMA techniques to reduce the component counts and the ultimate cost of the ground terminals. Incorporating the unique multiple digital beam forming technique with multiplexing provides contiguous multiple receive beams. The receiver monitors the signals from all the multiple beams simultaneously. The outputs of the digital multiple beamformer are then indexed through a set of orthogonal codes, such as hadema code, each of which represents the unique beam direction. By identifying the code of the signals locked onto the receiver, the location where the signal is coming from has been identified as well as the corresponding phase slope of the received aperture.

The transmit signal will be directed to the same antenna beam position from where the received signal originated. The transmit beam can then be steered by a phase conjunction mechanism. This multibeam beamforming and phase conjugation mechanism

using a Bulter matrix is described in U.S. Patent No. 4,812,788. However, the present mechanism is incorporated in digital form through FFT and is therefore uniquely different from a Bulter matrix. The transmit beam utilizes the phasing information, to perform a phase conjugation across the array element, and digitally multiply the outgoing signals with the conjugated phasing (equivalently perform a DFT to the signals on the array aperture). All the retrodirective functions can be accomplished in a very low power and low cost consumer digital electronics.

During an acquisition phase (from a cold start), all the received beams will be on to cover the entire field of view of the fan beam (almost all the elevation at a given azimuth angle). The mechanical search volume will be reduced to a one-dimensional (azmuthal) direction. With some knowledge of where the new satellite may come into the field of view, one may decide to only turn on the receive beams through the incoming direction.

Once the satellite link is established, the tracking mechanism is similar to that of a step scan principle. The signal strengths from adjacent received beams will be monitored and used to compare with the one coming from the main beam, the beam with the strongest signal will be identified as the locked (main) beam. As a satellite moves through from

horizon to horizon, a user terminal within the field of view (FOV) will switch the antenna to receive, and transmit beams from one position to another accordingly without conventional antenna tracking loops.

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As for equitorial non-geosynchronous constellations, users can use the disclosed terminal to avoid interruption during handover. During transition, there will be one satellite coming in and another satellite going out from a user's FOV. Furthermore, there is only a limited time window when the satellites are at the same elevation or near the same elevation, but at a different azimuth angle. The disclosed antenna can form two beams pointed towards these two satellites simultaneously. Consequently, it can provide the capability of "connect before break" during the hand over phase.

This low profile antenna configuration with a low profile randome may look like a thick pizza, and can be mounted on top of a moving vehicle, such as an automobile or an aircraft. This configuration can also be used as fixed user or mobile terminals for low earth orbit satellite constellations at L, S, Ku, and Ka frequency bands.

Having now fully described the invention, it will be apparent to one of ordinary skill in the art that many changes and modifications can be made

thereto without departing from the spirit or scope of the invention as set forth herein.